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Research Article

Determination of grid size for digital terrain modelling in landscape investigations—exemplified by soil moisture distribution at a micro-scale

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Abstract. The central problem of a combined analysis of digital terrain models (DTMs) and other landscape data is determination of a DTM grid size (w) providing a correct study of relationships between topographic variables and landscape properties. Generally, an 'adequate' w is determined by an expert estimate, and solutions are largely subjective. We developed an experimental statistical method to determine an adequate w for DTMs applied to landscape studies. The method includes the following steps: (*a*) derivation of a DTM set using a series of w_i, (*b*) performance of a correlation analysis of data on a landscape property and a topographic variable estimated with various w_i, (*c*) plotting of correlation coefficients obtained versus w, and (*d*) determination of smoothed plot portions indicating intervals of an adequate w. We applied the method developed to study the influence of topography on the spatial distribution of soil moisture (M) at a micro-scale. We investigated the dependence of M on gradient (G), horizontal (k_h), vertical (k_v), and mean (H) landsurface curvatures. For DTM derivation, we used 13 values of w_i from 1 to 7 m. An interval of adequate w_i for M falls between 2.25 and 3.25 m in the given terrain conditions. In absolute magnitudes, correlation coefficients are largest within this interval; correlation coefficients of M with G, k_h, k_v and H are -0.28, -0.52, -0.50 and -0.60, respectively, for $w = 3$ m. The results obtained demonstrate that the method actually works to identify an adequate w at a micro-scale. The method developed allows estimation of an adequate area of landform which 'realise' a topographic control of landscape properties.

1. Introduction

In landscape studies the question generally arises: What density of sampling points should be used to depict adequately the spatial distribution of a landscape property for a given scale, measurement accuracy, and minimum of samples (Lidov 1949, Kershaw and Looney 1985, Burrough 1993). If one carries out a study with a regular grid of sampling points, the problem reduces to determination of a grid size. Success of an investigation depends on the correct solution of this problem.

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The problem is connected with determination of a spatial scale of an object, phenomenon or process under study. This is a critical question because different physical laws and landscape processes dominate at different spatial scales. Extension of one or other conception or model to all scales can result in invalid description of actual relationships (Haggett *et al.* 1965, Klemes 1983, Phillips 1988, De Boer 1992).

An adequate description of a landscape property with a minimum of samples implies that a grid size corresponds to an area wherein which property values vary smoothly, or are assumed to have a constant value. These area and grid size will be denoted *the adequate area* of a landscape property and *the adequate grid size*, respectively (§2). In geomorphic and geological studies with digital terrain models (DTMs), one can determine an adequate grid size (w) of a DTM from a typical size of landforms or geological structures concerned (Evans 1972, Florinsky 1996). In studies of other landscape components (e.g. soils, plants) and landscape processes (e.g. lateral movement of substances in soils) determination of an adequate grid size is less trivial. This is due to large spatial variability of landscape properties (Kershaw and Looney 1985, Oliver and Webster 1986, Burrough 1993). In many cases, adequate areas are not correlated with 'basic' landscape units, such as stow and facies (Phillips 1988). In addition, a landscape property can offer several adequate areas connected with different natural processes (Sitnikov 1978, 1980, Kershaw and Looney 1985) (§2). There are some closely related methods to determine adequate areas in soils (Oliver and Webster 1986), plant (Kershaw and Looney 1985), hydrogeological (Sitnikov 1978, 1980), hydrological (Wood *et al.* 1988) studies. In these methods, an indicator of an adequate area is a smoothed portion of a plot describing a dependence of a property or its statistical parameter on area or grid size used for measurements of the property. Principles of these methods are detailed in §2.

The problem can be further complicated if one has to analyse data on two or more landscape properties in combination, or to predict one attribute through an analysis of another. This is because different landscape properties can be marked by different adequate areas (Phillips 1988). Besides, *a priori* existing relationships between two landscape properties (justified theoretically or observed in other landscapes) can be manifested at only certain adequate areas of these properties (Phillips 1988). For instance, it is well known that a watertable can look like a generalised landsurface. This regularity may be observed by an analysis of data on a watertable and a digital elevation model (DEM) with some w omitting relatively small topographic elements. However, one can find, at best, low correlation of the watertable with the topography using rather detailed or rather generalised DEM (Thompson and Moore 1996). Therefore, one may establish invalid statistical regularities (e.g. conservative correlation coefficients), incorrect predictions and conclusions for *a priori* related landscape properties, although one uses high-quality data on these properties. This problem is typical on an analysis of data marked by different resolutions and incongruent grids (Lidov 1949, Band and Moore 1995). However, the problem cannot be solved merely using data with like resolution and grid.

DTMs can be defined as digital representations of variables relating to a topographic surface, namely: DEMs, digital models of gradient (G), aspect (A), horizontal (k_h), vertical (k_v) and mean (H) landsurface curvatures, specific catchment area (CA), topographic index (TI) and some others (table 1) (Burrough 1986, Shary 1995). DTMs are commonly used in landscape studies since quantitative topographic characteristics are connected with some natural processes going on in a landscape and influencing its development (Moore *et al.* 1991, Shary *et al.* 1991, Florinsky

Table 1. Definitions and physical interpretations of some topographic variables (Florinsky and Kuryakova 1996, Florinsky 1998).

Topographic variables, unit	Definition	Physical interpretation
Gradient (G), °	An angle between a tangent plane and a horizontal one at a given point on the landsurface.	Velocity of substance flows.
Aspect (A), °	An angle clockwise from north to a projection of an external normal vector to a horizontal plane at a given point on the landsurface.	Direction of substance flows.
Vertical curvature (k_v), m^{-1}	A curvature of a normal section of the landsurface by a plane, including gravity acceleration vector at a given point.	Relative deceleration and acceleration of substance flows.
Horizontal curvature (k_h), m^{-1}	A curvature of a normal section of the landsurface. This section is orthogonal to the section of vertical curvature at a given point on the landsurface.	Convergence and divergence of substance flows.
Mean curvature (H), m^{-1}	A half-sum of horizontal and vertical curvatures.	Flow convergence and relative deceleration with equal weights.
Specific catchment area (CA), $m^2\, m^{-1}$	A ratio of an area of an exclusive figure, which is formed on the one hand by a contour intercept with a given point on the landsurface and, on the other by flow lines coming from the upslope to the ends of this contour intercept, to length of this intercept.	Contributing upslope area.
Topographic index (TI)	The Napierian logarithm of the specific catchment area-to-gradient ratio.	Extent of flow accumulation.

1998). Determination of a grid size is required in a combined analysis of DTMs and data on other landscape components (Moore *et al.* 1993, Quinn *et al.* 1995, Florinsky and Kuryakova 1996). Statistical characteristics of DTMs and the generalisation level of maps of topographic variables essentially depend on w (Evans 1980, Band and Moore 1995, Thompson and Moore 1996). Determination of w is generally solved by expert estimation (Anderson and Burt 1980, Moore *et al.* 1993) and so, solutions can be subjective. Besides, arbitrary choice of w can result in incorrect results and artefacts. For example, Speight (1980) did not find a relationship between soil moisture and k_h because in his study it was too small (Anderson and Burt 1980). Sinai *et al.* (1981) did not observe a correlation between soil salinisation and H. They explained the failure by w being too great and an incorrect choice of the study scale. In hydrological modelling based on TI, the average depth of the watertable decreases and the overland run-off increases when w increases (Wolock and Price 1994). The use of TI calculated with $w = 4$ m can result in the correct prediction of the watertable depth, while totally invalid prediction can be obtained using TI calculated with $w = 16$ m (Thompson and Moore 1996). Furthermore, slopes of DTM-based hydrographs essentially depend on w (Da Ros and Borga 1997).

Therefore, a correct choice of w is one of the main problems of DTM-based landscape investigations. However, the development of a method for an impartial determination of an adequate w remains an open question. In this paper, we present an experimental statistical method for the determination of an adequate w. Possibilities of the method proposed are exemplified by the topographic influence on the spatial distribution of surficial soil moisture at a micro-scale.

2. Theory

We propose an experimental statistical method for determination of an adequate w. The method is largely based on some principles of a conception of (representative) elementary volume used in mass transfer description, in particular, in hydrogeological studies (e.g. Sitnikov 1978, 1980). Some principles of this conception can be applied to solve a wide range of two-dimensional problems of geosciences if one switches from elementary volume to (representative) elementary area (e.g. Wood *et al.* 1988).

Assume that a response (figure 1(*a*)) describes the variation in the value of some landscape property (e.g. a rock property) with the volume or area for which the property is observed (Sitnikov 1978, 1980). Within the interval 1 the large extent of variability of property values can be a result of some pronounced spatial heterogeneity, for example, pore effects. Property values smoothly vary from the volume or area V_1 to V_2. Then another distinct spatial heterogeneity (e.g. macro-cracks) leads to abrupt variations of property values within the interval 3. Again, property values smoothly vary from the volume or area V_3 to V_4.

By the elementary volume or area we mean a minimum volume or area where a property is independent of heterogeneities, that is, the property values vary smoothly, or have a small variability (Sitnikov 1978, 1980). For instance, V_1 and V_3 are elementary volumes or areas for the given abstract property (figure 1(*a*)). Therefore, in some natural conditions for a landscape property one can distinguish a set of elementary volumes or areas connected with several intervals of smoothed relationships between property values and volume or area. Sometimes, intervals of smoothed variation of a landscape property cannot be found due to individual factors of natural processes as well as measurement errors (Sitnikov 1978, 1980).

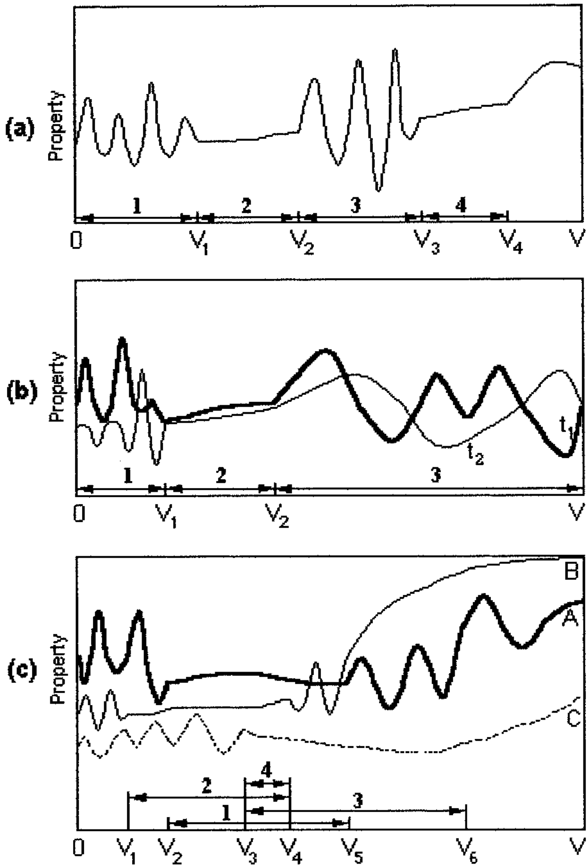

Figure 1. Possible dependence of an abstract landscape property on volume or area of observation (Sitnikov 1978, 1980): (*a*) dependence on volume or area, (*b*) dependence on volume or area at points in time t_1 and t_2, (*c*) dependence on volume or area for heterogeneous patches A, B and C.

An elementary volume or area can also depend on time through temporal variability of landscape properties (figure 1(*b*)) (Sitnikov 1978, 1980). In addition, an elementary volume or area of some property can depend on specific natural conditions. If a terrain includes heterogeneous patches, then a landscape property can be characterised by different elementary volumes or areas within adjacent patches. For example, assume that a terrain consists of three heterogeneous patches A, B and C. Assume that dependencies of property values on volume or area are smooth within intervals 1, 2 and 3 in patches A, B and C, correspondingly (figure 1(*c*)). Therefore, a property has elementary volumes or areas V_2, V_1 and V_3 in patches A, B and C, respectively. If one can find borders between the patches, it is desirable to study this property separately within each of the patches. However, one can observe the interval 4 wherein property values have low variability within all three patches (figure 1(*c*)). The elementary volume or area of this interval is V_3. It can be used as the common elementary volume or area for the overall terrain (Sitnikov 1978, 1980, Kershaw and Looney 1985).

By the adequate interval of volumes or areas we mean an interval of observation volumes or areas wherein property values smoothly vary, or have a constant value. Value variability can be ignored if it is not exceeded by investigation accuracy (Sitnikov 1980). For example, intervals 2 and 4 are adequate intervals of volumes or areas for the abstract landscape property discussed above (figure 1(*a*)). Adequate intervals of volumes or areas should be used for observations of landscape properties. Otherwise, one can obtain non-reproducible and poorly interpretable results due to large and unpredictable variability of property values within inadequate intervals of volumes or areas.

By the adequate volume or area we mean a volume or an area belonging to an adequate interval of volumes or areas (Sitnikov 1978, 1980). By the adequate grid size we mean a grid size corresponding to an adequate area. With the Kotelnikov theorem (Korn and Korn 1968), a continuous function $f=f(x, y)$ with border frequencies $F_x = F_y = 1/s$ can be uniquely determined by its values with sampling step $s/2$ where s is the smallest planimetric size of elements of the surface $f=f(x, y)$ of interest to a user. Therefore, if s^2 is the adequate area of a landscape property, then $s/2$ is the adequate grid size relating to s^2 and providing adequate description of this property.

An adequate grid size can be defined by (*a*) measurement of a landscape property at grid nodes using different grid sizes, and (*b*) plotting values measured against grid sizes (similarly to figure 1(*a*)). Smoothed portions of this plot will indicate intervals of adequate grid sizes (Sitnikov 1980). On determination of the adequate grid size, one can readily evaluate a related adequate area of a landscape property (see above).

In a combined analysis of two landscape properties and in a prediction of one property by an analysis of the other property, one should work in an adequate interval of areas, which is common to both properties. Values of both properties are constant or smoothly vary within this interval, by definition of the adequate interval (see above). Therefore, correlation coefficients between values of two properties can also smoothly vary within the common adequate interval. At the same time, one can observe large variability of correlation between two properties within adjacent inadequate intervals marked by large variability of property values. So, to determine a common adequate interval of areas and grid sizes providing an adequate combined study of two properties, one should (*a*) analyse the correlation between these properties observed with different grid sizes, and (*b*) plot correlation coefficients obtained versus grid sizes. A smoothed portion of this plot can indicate an interval of adequate grid sizes and hence an adequate interval of areas which is common to both landscape properties.

By the adequate w we mean the adequate grid size if a topographic variable described as a DTM is one of two landscape properties under study. The adequate area corresponding to the adequate w determines a typical size of landforms providing a topographic control of a landscape property concerned. To define the adequate w one should carry out the following procedures:

- To derive a set of DTMs using a series of w_i;
- To perform a correlation analysis of data on a landscape property and a topographic variable estimated with various w_i;
- To plot correlation coefficients between the landscape property and the topographic variable versus w_i;
- To determine smoothed portions of the plot obtained which indicate intervals of adequate w_i.

There are three main variants for implementation of the method proposed depending to formats of initial data:

1. DEM and data on landscape property are obtained using coincident square grids with grid size of w. One can then derive a set of digital models of a topographic variable concerned from the DEM by accessible methods (Evans 1980, Quinn *et al.* 1995) using grid sizes of w, $2w$, $3w$, ..., nw where n is an integer. Then one should analyse a correlation between the landscape property and the topographic variable using samples with grid sizes of w, $2w$, $3w$, ..., nw.
2. DEM and data on landscape property are obtained using distinct grids and then interpolated (Watson 1992) to a common square grid with a grid size of w. Further steps are the same as in the first variant.
3. DEM and data on landscape property are obtained using distinct grids, and spatial interpolation of data on landscape property is undesirable or impossible (e.g. landscape data are collected along a transect or a contour—§4). One should (*a*) produce several DEMs with different w_i by interpolation (Watson 1992), (*b*) derive a topographic variable concerned from these DEMs, (*c*) interpolate values of the topographic variable calculated with different w_i for points in which the landscape property was observed, and (*d*) analyse a correlation between the landscape property and the topographic variable calculated with different w_i.

From the viewpoint of minimisation of interpolation errors (Watson 1992), the first variant of the method of implementation is the best since interpolation is not used. Next is the third variant in which one should interpolate only DTMs. The second variant including interpolation of both DTMs and data on landscape property may result in the greatest frequency of interpolation errors. In this study, we used the third variant of implementation of the method due to the format of initial data (§4).

Different topographic variables can be connected with landscape processes of different scales (Anderson and Burt 1980, Florinsky and Kuryakova 1996). Thus, a landscape property can be 'controlled' by different topographic attributes at different adequate areas. Therefore, different topographic variables can offer different adequate w_i suited for each landscape property. In landscape studies, particularly in the determination of a regression equation for dependence of a landscape property on topographic variables, it is desirable to find the 'main' interval of an adequate w common to all topographic variables under consideration. Obviously, it makes sense to perform a regression analysis only with an adequate w of this interval.

3. Study site

The study site is located at the centre of the East European Plain, to the south of the Moscow Region, Russia, near the City of Pushchino (figure 2). It is a zone of a temperate continental climate with warm summers and prolonged cold winters. January and July average temperatures are -10°C and 18.6°C, correspondingly. Precipitation is about 640 mm per year, of which 350–450 mm are rainfall.

The site is situated on the soddy and partially forested landslide macroslope of the valley of the Oka River. Elevations are about 130 m above sea level. The macroslope is characterised by an average gradient of 10° and a northerly aspect. Middle Carboniferous fractured and karstified limestone lie at a depth of about 6 m.

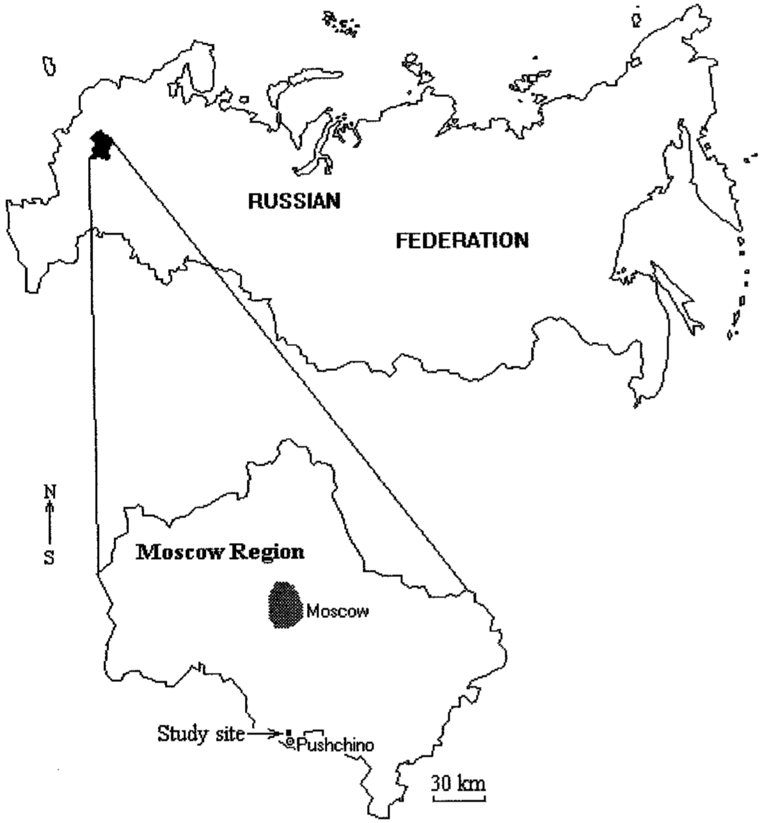

Figure 2. Geographical location of the study site (37°34′30″ N, 54°41′10″ E).

Quaternary loams cover them. Groundwater lies at a depth of about 6 m (Lyubashin and Lisitsin 1981).

The study site measures about 58 by 77 m and includes a part of a north-striking gully; variation in altitude is about 15 m (figure 3(*b*)). The soil complex includes grey

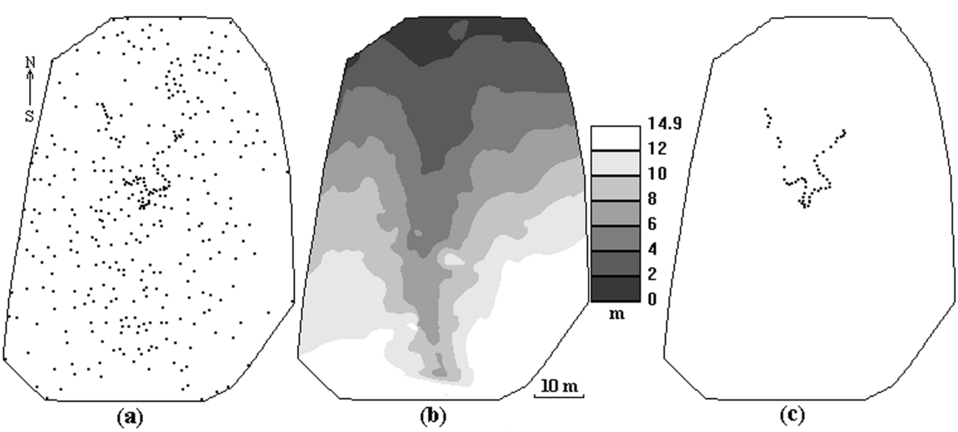

Figure 3. The study site: (*a*) spatial distribution of tacheometer points, (*b*) map of elevation, (*c*) location of soil samples along the 4.25 m contour.

forest soils on crests and slopes, and meadow hydromorphic soils in the valley bottom. Vegetation cover consists of birches and herbs on crests, hazels and common horsetails on slopes, and nettles in the valley bottom. There is significant diversity of topographic variables and moistening of the soil cover within a small area of the study site.

4. Materials and methods

We obtained an irregular DEM of the study site by a tacheometric survey with a tacheometer TaN. The irregular DEM consists of 374 points (figure 3(*a*)). It is constructed in a relative Cartesian co-ordinate system and in a local elevation system. We used the minimal value of the landsurface elevation within the study site as the local datum (figure 3(*b*)).

To estimate surficial soil moisture (M) we carried out a soil survey on 20 June 1990. Precipitation was about 60 mm from 1–20 June 1990 in Pushchino and suburb. There was drizzling rain (about 2 mm) on the eve of the soil survey. To prevent a significant influence of evaporation on M we performed the soil survey in the morning within one hour at the air temperature of 20–22°C. The soil survey included sampling at 62 points (all included in the irregular DEM) which are located along the 4.25 m contour (figure 3(*c*)). These points are rather evenly distributed along the contour with a distance ranging from 0.5 to 1.5 m. To the west side of the gully, three larger distances correspond to two tree-falls and a track (figure 3(*c*)). We took three soil samples at each of the 62 points at a depth of about 0.1 m (altogether, there were 186 samples). We evaluated M for each of these samples by weighing pre- and post-drying samples on an analytical damper balance ADV-200. Drying of samples was carried out by a drying box 2V-151 for 12 hours at 100°C (Arinushkina 1962). To reduce influence of random deviations of M values, we used the arithmetic mean of M for the three samples collected in each of 62 points as net values of M (figure 4).

We carried out soil sampling along one contour to eliminate *apparent* influence of elevation (h) on M from consideration. Obviously, actual influence of h on M observed in mountainous regions due to the altitudinal zonality cannot occur within the study site. G, A, k_h, k_v, H, and CA are responsible for physical mechanisms of distribution and redistribution of moisture in landscapes (table 1). Dependence of M on h observed in plain landscapes is in fact a result of the influence of CA on M.

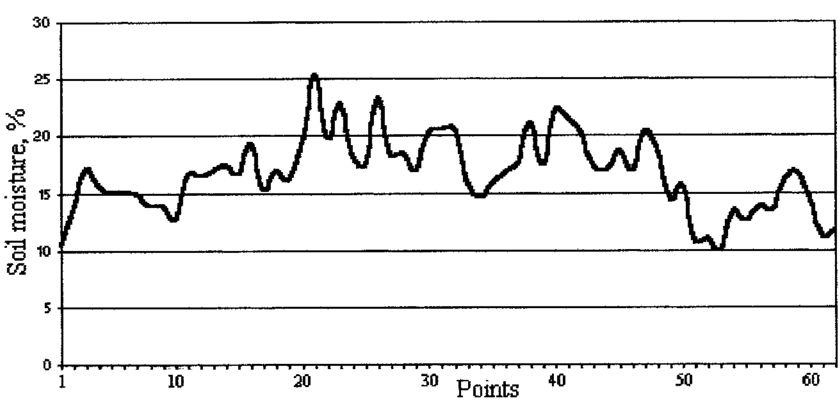

Figure 4. Distribution of surficial soil moisture along the contour of 4.25 m.

This is because h is not responsible in itself for physical mechanisms of gravity-driven moisture movement (table 1). However, h is taken into account in the calculation of CA in a hidden form (Quinn *et al.* 1995).

We chose the contour of 4.25 m because (*a*) it passes over the main landforms within the site: two crests, slopes, and the gully bottom (figure 3(*b*) and (*c*)), and (*b*) it is suitable for the soil survey because higher elevation slopes are too steep. Notice that although we used distinct grids for the soil and topographic surveys, in the general case it is desirable to use identical grids (ideally, square grids) for these purposes.

Using the Delaunay triangulation and a piecewise smooth interpolation (Watson 1992) of the irregular DEM, we produced 13 square-gridded DEMs with the following w_i (in brackets are numbers of points in regular DEMs): 1 m (3312), 1.5 m (1421), 2 m (742), 2.5 m (461), 3 m (301), 3.5 m (202), 4 m (152), 4.5 m (110), 5 m (85), 5.5 m (63), 6 m (48), 6.5 m (35), and 7 m (31). We decided on this range of w from the following reasons. To estimate local topographic variables one has to calculate the first and the second derivaties of elevation (Evans 1980, Shary 1991, 1995). These calculations increase errors of DEM compilation and interpolation (Giles and Franklin 1996). Our experience and preliminary testing of the irregular DEM of the study site (figure 3(*a*) and (*b*)) suggest that these errors can be ignored, in this case, when $w \geqslant 1$ m. Considering the size of the study site, $w = 7$ m is the maximum w which can be used to derive local topographic variables. $\Delta w = 0.5$ m was of interest, and its use allowed us to determine the adequate w for the study study (§5).

Digital models of G, k_h, k_v and H were derived from all 13 regular DEMs by the method of Evans (1980) (figure 5). Altogether, we produced 52 regular DTMs. Then we used the Delaunay triangulation and a piecewise smooth interpolation (Watson 1992) of these 52 regular DTMs to determine values of G, k_h, k_v and H corresponding to planimetric co-ordinates of the 62 points on the 4.25 m contour.

To determine an adequate w and to estimate the dependence of M on topographic variables we carried out a linear multiple correlation analysis of M with G, k_h, k_v and H calculated for the 13 values of w_i. 62-point samples were used for DTMs with $w = 1$, ..., 5 m, 59-point samples for DTMs with $w = 5.5$ and 6.5 m, 56-point samples for DTMs with $w = 6$ m, and 53-point samples for DTMs with $w = 7$ m (border effects were omitted). With the method proposed (§2), we presented the dependence of correlation coefficients on w in the form of plots for G, k_h, k_v and H. To describe an effect of topography on the distribution of M, the 'best' combination of topographic variables was chosen by the stepwise linear regression (Aivazyan *et al.* 1985). We used the 62-point samples corresponding to the two adequate w_i determined (§5) for regression analysis.

We did not study the influence of A on M since the study site is located (*a*) on a macroscope with a uniform northerly aspect, and (*b*) in forest where sunlight is diffused by trees. Therefore, we can consider A as a background fixed value in the study site, although the dependence of M on A is generally apparent (Zakharov 1940). In addition, we did not study the influence of CA on M since we did not perform the tacheometric survey for a gully head and derivation of CA from DEMs without data on catchment heads can lead to invalid results.

We applied the software LANDLORD 2.0 (Florinsky *et al.* 1995) for the irregular DEM interpolation, topographic variables' calculation and mapping (figures 3 and 5). Correlation and regression analyses were carried out with STATGRAPHICS 2.6.

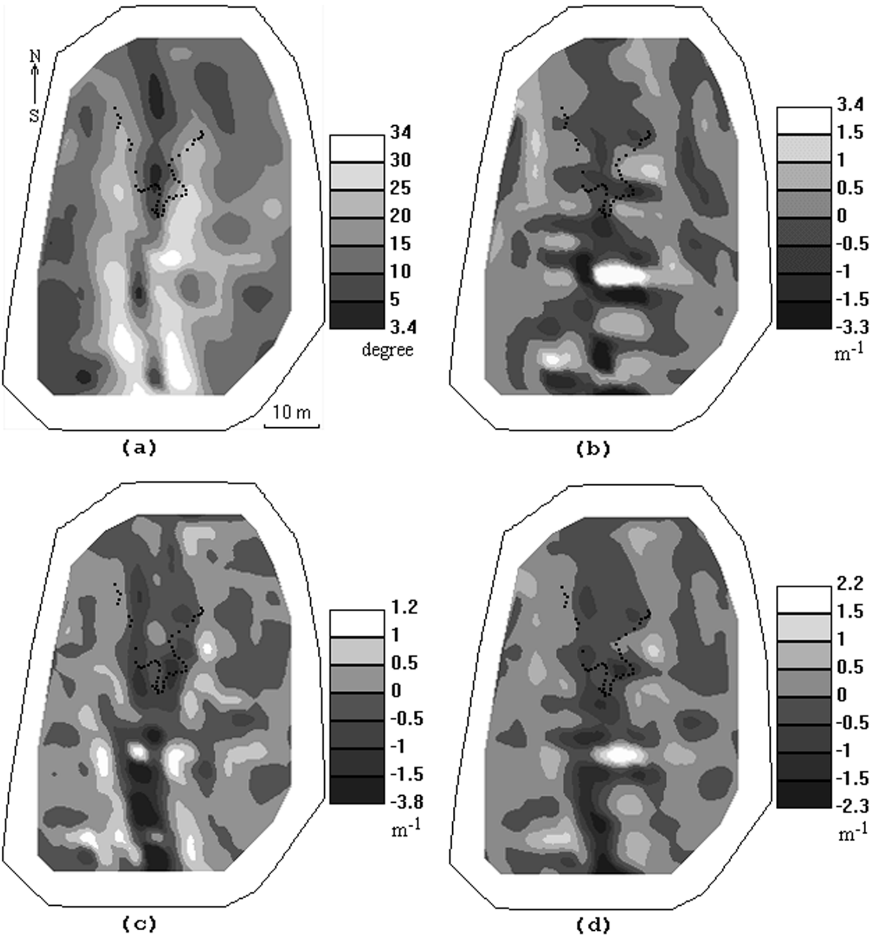

Figure 5. Maps of local topographic variables derived from the DEM with $w = 3$ m: (*a*) gradient, (*b*) horizontal curvature, (*c*) vertical curvature, (*d*) mean curvature; dots are locations of soil samples along the 4.25 m contour.

5. Results and discussion

Results of the correlation analysis are presented in table 2. Figure 6 gives plots of correlation coefficients between M and G, k_h, k_v and H versus w. As expected, these plots include some portions of smoothed variation of correlation coefficients with w as well as some portions of large variability of this relationship (figure 6). All four plots present two main portions: the left portion (between $w = 1$ m and $w \cong 4$ m) with relatively smoothed variations, and the right portion (between $w \cong 4$ m and $w = 7$ m) with pronounced fluctuations. With the method developed (§2), using smoothed portions of the plots obtained as indicators of adequate intervals of w we can distinguish:

- The adequate interval W_1 for H, k_v and k_h ranging between $w \cong 2.25$ and $w \cong 4$ m, and
- The adequate interval W_2 for G, H, k_v and k_h, ranging between $w \cong 2.25$ and $w \cong 3.25$ m.

Table 2. Point and interval estimates of pairwise coefficients of linear correlation between surficial soil moisture and some topographic variables for different values of w_i (values in brackets are significance levels).

Topographic variables	w_i, m												
	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
G	− 0.29	− 0.24	− 0.16	− 0.32	− 0.28	− 0.04	0.06	0.34	0.24	0.06	0.58	0.13	0.05
	(0.02)	(0.06)	(0.21)	(0.01)	(0.03)	(0.77)	(0.64)	(0.01)	(0.06)	(0.65)	(0.00)	(0.31)	(0.73)
k_h	− 0.12	− 0.06	− 0.34	− 0.38	− 0.52	− 0.36	− 0.36	− 0.06	− 0.35	− 0.15	− 0.29	− 0.15	− 0.42
	(0.34)	(0.67)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.65)	(0.01)	(0.24)	(0.03)	(0.24)	(0.00)
k_v	− 0.32	− 0.40	− 0.37	− 0.53	− 0.50	− 0.44	− 0.47	− 0.19	− 0.52	− 0.18	− 0.53	− 0.04	− 0.33
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.14)	(0.00)	(0.17)	(0.00)	(0.79)	(0.02)
H	− 0.27	− 0.29	− 0.46	− 0.58	− 0.60	− 0.53	− 0.49	− 0.16	− 0.46	− 0.17	− 0.41	− 0.10	− 0.39
	(0.04)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.22)	(0.00)	(0.19)	(0.00)	(0.44)	(0.00)

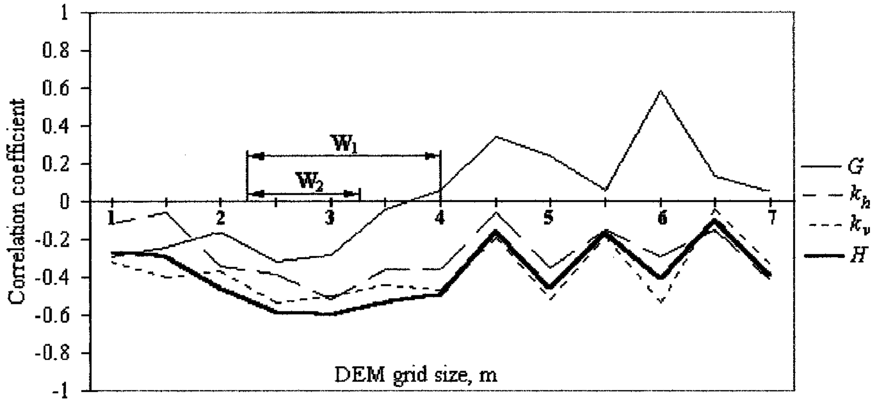

Figure 6. Correlation between surficial soil moisture and topographic variables versus w.

W_2 is the 'main' adequate interval of w because all correlations peak there (except 'spurious' correlations of M with G for $w = 4.5$ and 6 m—see explanation below). For example, for $w = 3$ m correlation coefficients of M with G, k_h, k_v and H are -0.28, -0.52, -0.50 and -0.60, respectively (table 2).

Generally, these results conform to established data on the topographic control of soil moisture. Indeed, as G increases, velocity of water flow and slope area increase, so the rainfall received per unit area and its infiltration decrease, while the runoff and evaporation area increase, and hence soil moisture decreases (Zakharov 1940). In addition, the soil moisture and the lateral intrasoil flow of the saturated zone increase when $k_h < 0$ (areas of flow convergence) and decrease when $k_h > 0$ (areas of flow divergence) (Kirkby and Chorley 1967). Besides, k_h influences hydrological processes within unsaturated rocks: streamlines diverge when $k_h > 0$ and converge when $k_h < 0$ (Zaslavsky and Rogowski 1969). Saturation zones and source areas of overland flow correlate with landforms where both k_h and k_v have negative values (areas of flow convergence and relative declaration, correspondingly) owing to increased soil moistening (Wood *et al.* 1990, Feranec *et al.* 1991). It is reasonable that we observed the strongest correlation between M and H: H is a half-sum of k_h and k_v, that is, H presents k_h and k_v with equal weights (table 1). Therefore, H can be more a representative topographic attribute than k_h and k_v in relation to description of landscape processes. The high linear correlation (-0.9) of M with H was observed by Sinai *et al.* (1981) in the arid climate and the flat topography of Israel deserts. These authors suggested that this dependence is the result of topographic control on the intrasoil lateral water movement rather than the redistribution of overland water flows by microtopography since the latest process is not typical for the landscape concerned. Correlation coefficients relevant to adequate w_i (table 2) testify that M depends on landsurface curvatures largely than G within the study site. So, M is controlled predominantly by convergence and relative deceleration of overland and intrasoil water flows.

Intervals of inadequate w_i differ greatly in appearance from adequate intervals of w_i: there are drastic variations of the dependence of correlation coefficients on w (figure 6). Besides, within the inadequate interval of w_i (between $w \cong 4$ m and $w = 7$ m) correlations of M with k_h and H are much lower than within the main adequate interval (figure 6 and table 2). Moreover, within this inadequate interval of w_i we observe positive correlations between M and G, and not just fluctuations of the associated plot (figure 6 and table 2). This is the evident artefact caused by the use of an inadequate w. Indeed, the moisture of the soil cover decreases when G increases (see above). So, if there is a dependence of M on G in the given conditions and scale, correlation coefficients between M and G can take only negative values, as we found for $w = 1$–3.5 m (table 2 and figure 6). This demonstrates the importance of the correct determination of w to the validity of an investigation. In addition, this is a pictorial example of how one may obtain invalid conclusions using statistics only, without realisation of the physical expression of topographic variables and relationships between topography and landscape processes.

Results of the regression analysis are presented in table 3. We obtained regression equations for two adequate $w = 2.5$ m and 3 m. In both cases, G and H entered the equations as independent variables. We suppose that k_h and k_v did not enter the equations since H presents these topographic attributes with equal weights (table 1). The regression equations describe 45% and 39% of variability in M for $w = 2.5$ m and $w = 3$ m, respectively (table 3). These R^2 values are not high. Possibly, this is because we did not analyse the dependence of M on CA effecting essentially the spatial distribution of soil moisture (Zakharov 1940, Speight 1980). CA describes quantitatively the three-dimensional position of a point on a slope (slope length describes a position of a point on a slope for a two-dimensional case). We did not use CA data since derivation of CA from DEMs without data on catchment heads can lead to invalid results (§4).

One may use regression equations (table 3) in DTM-based predictive mapping of M using associated adequate w_i. Data on M can be useful, for instance, in predicting the evaporation from the soil surface (Camillo and Gurney 1986) and modelling the soil water balance (Bruckler and Witono 1989). Predictive mapping of M using DTM-based regression equations can be valuable, in particular, in forested terrains where other techniques of M evaluating (e.g. radar survey, Bruckler and Witono 1989) are complicated to apply.

The method developed allows one to estimate not only adequate w_i, but an adequate area of landforms 'realising' a topographic control of landscape properties as well. From the relation between an adequate area and an adequate grid size (§2), the adequate area of landforms controlling M lie in the range from 20 to 40 m^2 within the study site. Notice that the adequate $w \cong 3$ m is close to $w = 4$ m providing a correct prediction of the watertable depth using TI (Thompson and Moore 1996). This can indicate that the topographic control of some soil-hydrological processes occurs on landforms with the adequate area ranging between 36 and 64 m^2 in

Table 3. Parameters of regression equations describing the dependence of surficial soil moisture on topographic variables for adequate w_i.

w_i, m	Independent variables	Coefficient	Significance level	R^2
2.5	G	− 0.20	0.00	0.45
	H	− 4.77	0.00	
	Constant	18.05	0.00	
3.0	G	− 0.14	0.02	0.39
	H	− 5.16	0.00	
	Constant	17.13	0.00	

subboreal regions. Therefore, 3–4 m may be suitable values of the adequate w for DTM-based soil and hydrological studies in these climatic conditions.

Notice that one should use the adequate w_i found with caution in soil moisture studies in other terrains and at other scales because the study site is too small. However, the results obtained demonstrate that the method actually works to identify adequate w_i, at least at a micro-scale. We suppose that the method can be used in other types and sizes of terrains without fundamental problems. Some difficulties can arise if a large study area includes some heterogeneous patches, which may be marked by dissimilar relations between topography and a landscape property. In this case, it is desirable to apply the method to each patch separately and to determine adequate w_i for each patch.

A weakness of the method proposed is subjectivity of the partititon of the correlation coefficient curves into adequate and inadequate (smooth and variable) intervals. This is because these curves have no clear-cut 'boundaries' between adjacent intervals. This weakness can be fixed using some thresholds for an increment or a decrement of a function describing a dependence of correlation coefficients on w. The other bottleneck of the method is the choice of the minimum w and Δw. Analysing the plots obtained (figure 6), it is not difficult to see that if we used $\Delta w = 1$ m, we would not find fluctuations of the dependence of correlation coefficients on w within the right inadequate interval of w_i (between $w \cong 4$ m and $w = 7$ m). Using $\Delta w = 1$ m, these fluctuations cannot be found with the minimum w of both 1 m and 1.5 m (although these plots would differ noticeably from one another). Based on the results obtained, we suppose that for a minimum w one should use w such that DTM errors caused by calculation of elevation derivatives (§4) can be ignored. Δw should be less than a half of the minimum w.

It is conceivable that plots of correlation coefficients between a landscape property and topographic attributes versus w may include smoothed portions, but correlations may be very low in absolute magnitude. This result may demonstrate that while the landscape property is influenced by landforms with typical sizes related to intervals of adequate w_i, this is a slight dependence.

In this work, we used a linear correlation analysis (§4). However, it is more likely that actual relatinships between topography and other landscape components have a non-linear character. Besides, statistical distributions of topographic variables are slightly different from normality (Evans 1980). Therefore, it can be more correct not to work with coefficients but with indices of correlation (Aivazyan *et al.* 1985).

We did not study a dependence of the adequate w_i on time (§2) because we have no data on the dynamics of M within the study site. This is a subject of further investigations.

6. Conclusions

1. We developed an experimental statistical method to determine adequate w_i for digital terrain modelling in landscape studies. The method includes the following steps: (*a*) derive a set of DTMs using a series of w_i, (*b*) perform a correlation analysis of data on a landscape property and a topographic variable estimated with various w_i, (*c*) plot correlation coefficients obtained versus w, and (*d*) determine smoothed plot portions indicating intervals of adequate w_i.

2. With the method developed, the interval of adequate w_i for M falls in the range between 2.25 and 3.25 m in the study site. In absolute magnitudes, correlation

coefficients peak within this interval. In particular, correlation coefficients of M with G, k_h, k_v and H are -0.28, -0.52, -0.50 and -0.60, correspondingly, for $w = 3$ m.

3. The method developed allows one to estimate an adequate area of landforms 'realising' a topographic control of landscape properties. The adequate area of landforms controlling M lie in the range from 20 to 40 m^2 within the study site.

4. The results obtained demonstrate that the method actually works to identify adequate w_i, at least at a micro-scale, and may improve impartiality of DTM-based landscape investigations.

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